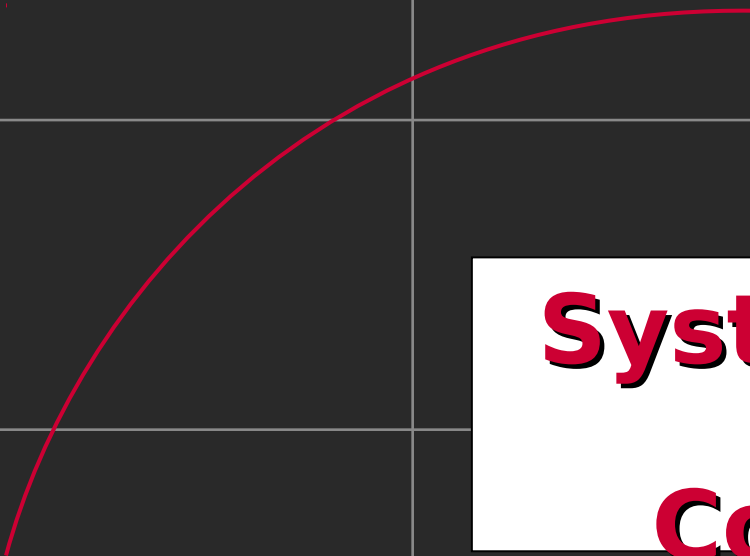
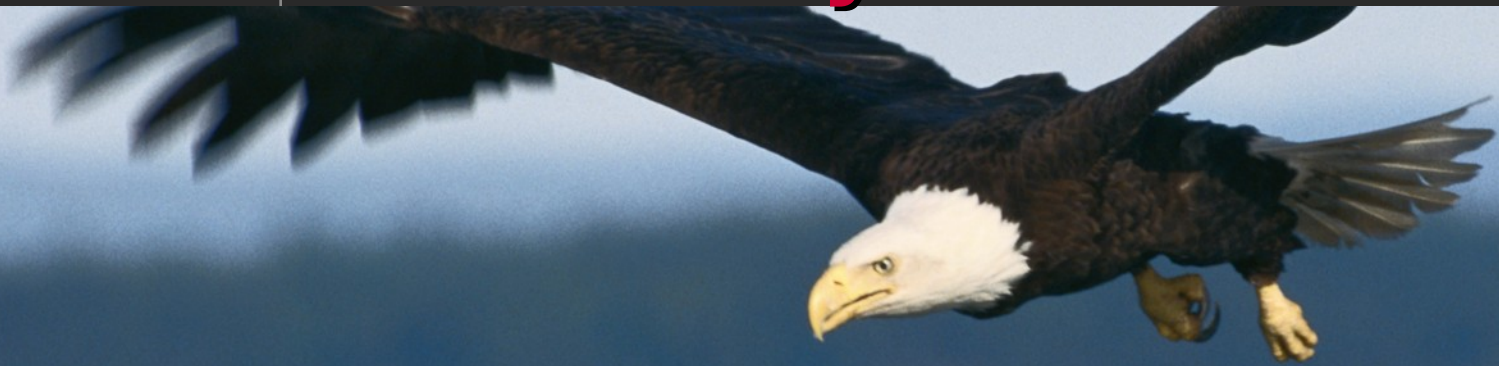




Systems Engineering of Complex Adaptive Systems



**National Defense Industrial
Association**

**6th Annual Systems Engineering
Conference (Oct. 2003 San Diego)**

Otto Jons

CSC

EXPERIENCE. RESULTS.

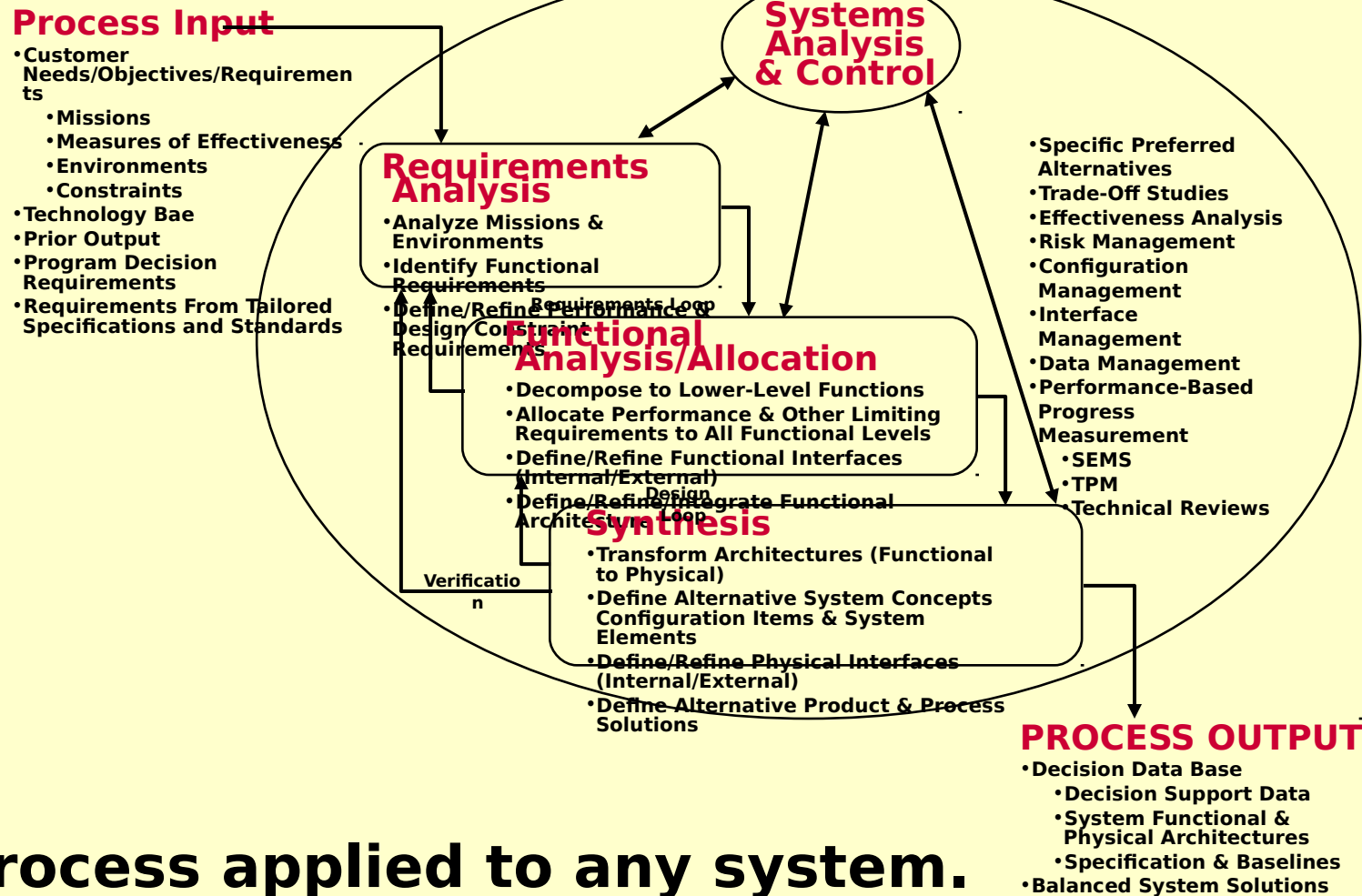
- **A rigorous scientific basis for Complex Adaptive Systems: - Still in its infancy**
- **Popular science flavor of books by Gleick (“Chaos”) and Waldrop (“Complexity”): - Disdain (?) by some “serious” scientists and engineers**
- **Some advances by scientists: See Holland (“Hidden Order” and “Emergence”)**

However:

- **Complex Adaptive System: - Profoundly important**
- **Some “lessons (-ready to be-) learned”**

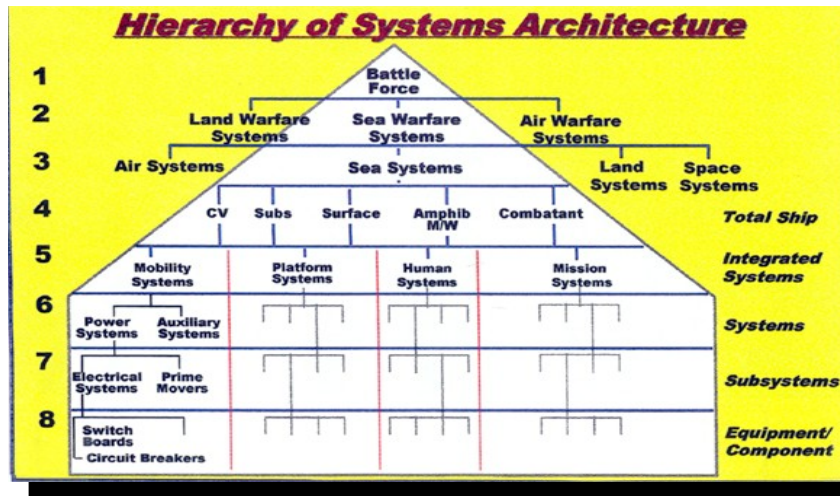
- **Systems Engineering:
- A Very Brief
Review**
- **The Systems Spectrum**
- **Complex Adaptive Systems**
- **Developing (Elements of)
CAS**
- **Summary and Conclusions**

Current doctrine has matured into a standard process,



-a process applied to any system.

System Hierarchies: The Vertical Dimension



- Nation
- Government
- DoD/Navy
- Joint Force
- Battle/Task Group
- Ship
- Machinery System
- Propulsion System
- Engine
- Fuel Pump

How about the Horizontal
Dimension ??

Are there different System



- **Systems Engineering - A Brief Review**
- **The Systems Spectrum:**
 - **Spectrum Samples**
 - **The Limits of Engineering**

***From Newtonian
Physics***

***A Brief
Tutorial***

To “New Science”

- **Traditional Engineering Systems (TES)**

=Newtonian/Mechanistic:

=“Action equals Reaction”, etc.

=The Foundation of Technology



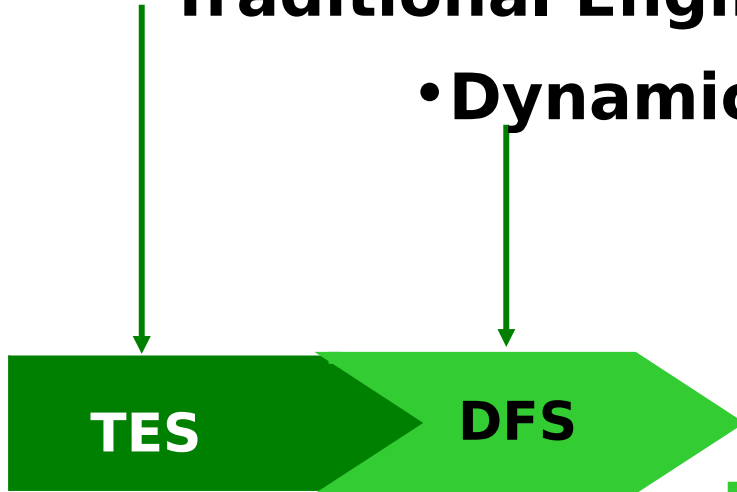
TES

- ***Current SE Doctrine focuses (-exclusively??) on TES:***

- ***Development of an Optimal System for a Specified Need / Operation***

- **Traditional Engineering Systems**

- **Dynamic Feedback Systems**



e.g., Double Pendulum; - seemingly simple, but.....

- **Traditional Engineering Systems**

Dynamic Feedback Systems

**Complex “Chaotic”
Systems**



***e.g., Weather System; highly complex,
also involving dynamic feed-back***

- **Traditional Engineering Systems**

- **Dynamic Feedback Systems***

- **Complex “Chaotic” Systems****



***- DFS & CCS obey the laws of physics,
however: Prediction of long-term behavior
not possible because of extreme sensitivity
to initial conditions***

- **Traditional Engineering Systems**

- **Dynamic Feedback Systems***

- **Complex “Chaotic” Systems****



Complex Adaptive Systems

= Characterized by “Adaptive Agents”

- **Traditional Engineering Systems**

- **Dynamic Feedback Systems***

- **Complex “Chaotic” Systems****



Complex Adaptive Systems:
Reactive CAS

= Ecology; Natural systems, such as the Immune System;

- **Traditional Engineering Systems**

- **Dynamic Feedback Systems***

- **Complex “Chaotic” Systems****



Complex Adaptive Systems:

Reactive CAS

Proactive CAS

**=Economies, Games, Conflicts, Warfare:
Conscious decision-making by
intelligent agents**

- **Engineering (-and Systems Engineering), to date: Focus almost exclusively on TES**
- **Traditional engineering encounters increasing limitations**



- **Warfare Systems are generally P-CAS**
- **They may be R-CAS if threat-based**
- **They may have TES - or R-CAS subsystems**

Traditional Engineering Systems

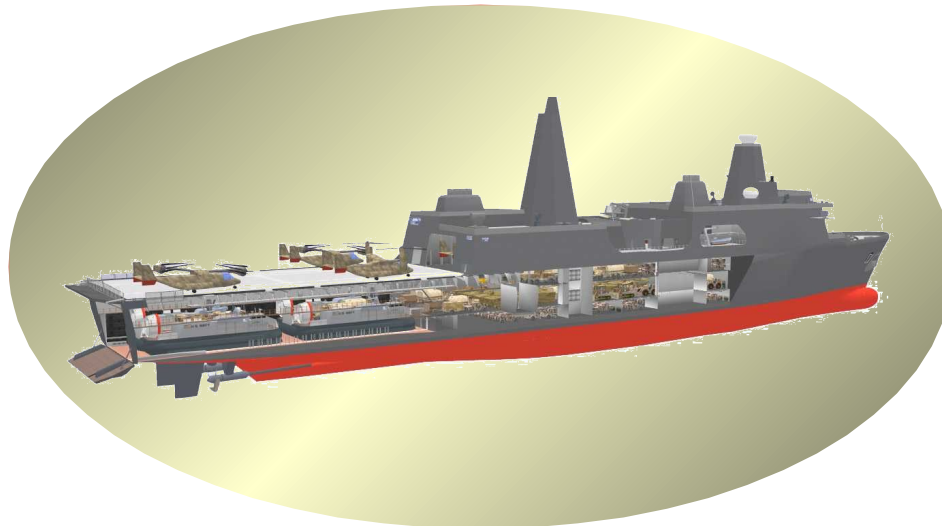


Proactive CAS



Explore differences between TES & P-CAS:

Use the *Naval Ship System*:



- Sheer Size & High Cost:
~ i.e., No Prototyping
- Long Life Span:
~ 40+ Years

The Naval Ship System: A Hybrid System



The Hull: A Transportation System

The Weapon Suit: A Warfare System
(Often with a Transportation Subsystem)

- ***40+ Years Lifespan***
- ***(Generally:)***

***Mature
Technology***

- ***2 to 10 Years Lifespan***
- ***(Generally:)***

***Advanced
Technology***

The Naval Ship System: A Hybrid System



In Part = A Transportation System

*In Part = (Part of) a Warfare System
(Often with a Transportation Subsystem)*

These Differences :

- Manifest themselves in the ways **Effectiveness** is established
- Warrant differing development approaches

(A Shuttle Ship: A pure **Transportation System**:)

$$\text{Effectiveness (E)} = \frac{\text{Payload (P) X Distance (D)}}{\text{Time (T)}}$$

$$\begin{aligned} E &= P \times D / (T_p + T_s) \\ &= P \times D / (T_p + D / V) \end{aligned}$$

Where: T_p - Time in Port

T_s - Time @ Sea

V - Speed

Note: - A Mathematical Relationship can be established between System Performance and Effectiveness.

- The Objective is achieved largely by the System's **Output**.

- **Systems Engineering - A Brief Review**
- ➔ • **The Systems Spectrum:**
- **Complex Adaptive Systems (CAS):**
 - **Effectiveness of P-CAS**
 - **Adaptation / Implication for Warfare Systems**

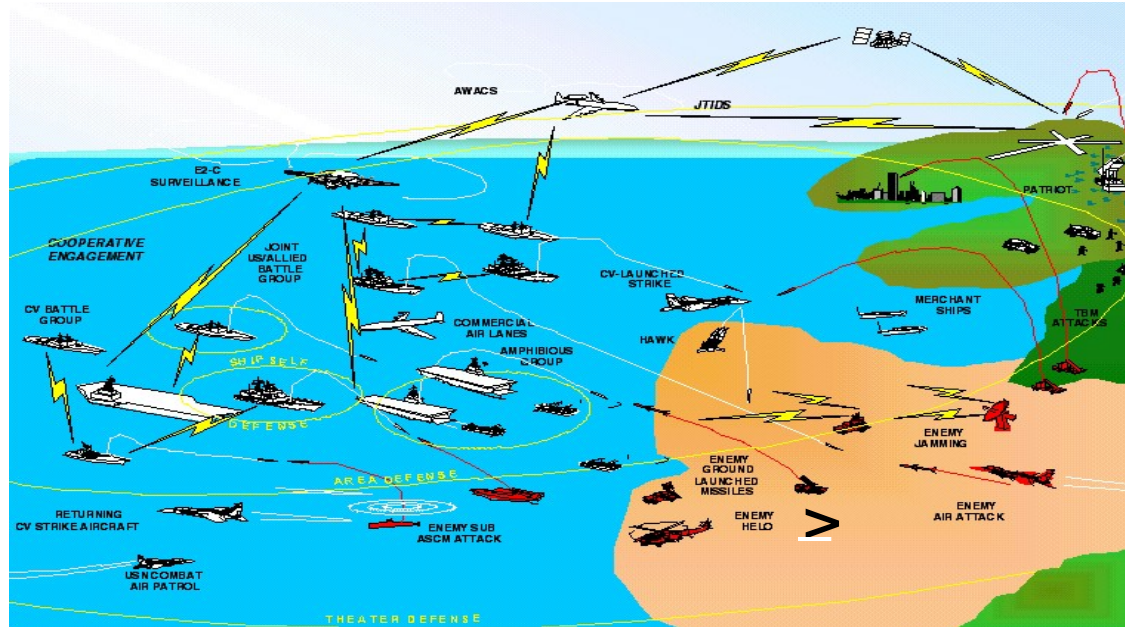
Effectiveness of P-CAS



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Mission Success / Effectiveness: **Outcome** (Not: Output)

Planned Outcome

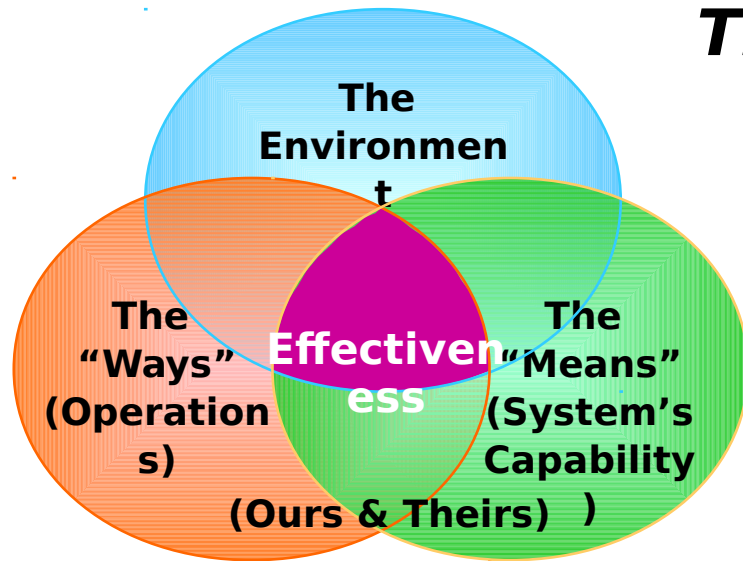


Actual Outcome

Mission Success : Planned Outcome $\leq$ Actual Outcome

Parameters:

- Systems Deployed (The “Means”) & Their Capability
- Strategies, Tactics, CONOPS (The “Ways”)
- The Environment/ its Effect on “Means” and “Ways” (“Ways” & “Means”: Both “Ours -” & Theirs -)



The Goal:

Accomplishing an Objective:

= Winning a Battle

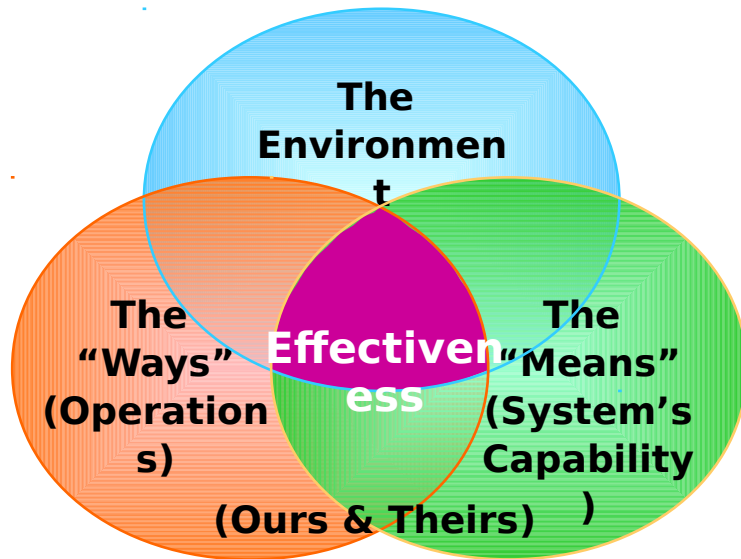
= Succeeding in ...

...(Name it)

= Winning a Game of

...Chess where:

- The **"Environment"** (Board) is fixed
- The **"Means"**: The Performance Capabilities of the pieces are defined and fixed
- **Effectiveness** (= Winning) is then solely a function of the players' **"Ways"**: How they play, react to and anticipate the opponent's moves



(Another Example:)

The Mission:
Winning a Football Game

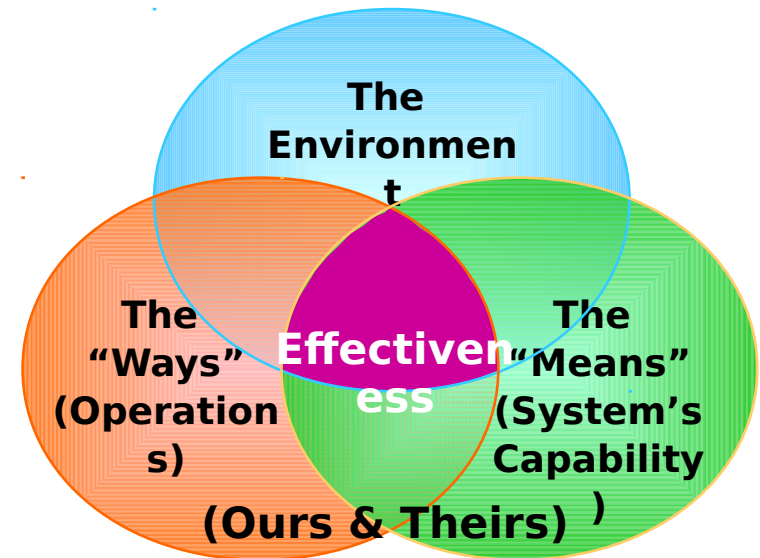
- The **"Environment"/Field** is Fixed and Further Neutralized by Switching Sides at Halftime
- The **"Means"**: The Performance Capabilities of the Teams, as Units (Offensive -, Defensive - and Special Teams) , Individuals, Their Natural Ability, Conditioning, Training,
- The **"Ways"** involve the Play-Book, the Plays Called and the Reaction of the Defense

• **Effectiveness (= Winning)** is a Function of "Winning"

- **Proactive Adaptation in Warfare:**
 - All about the Creation of Asymmetries (= greater strength at the point of contact)
- **Asymmetries may be created**
 - “Locally”; - in the same general physical environment (maneuver warfare)
 - In an entirely different environment
- **Adaptation: More likely to be effective if it is not anticipated by the adversary**
- **Warfare: Need not be proactive-adaptive; May be re-active-adaptive**
- **Sun Tzu’s teachings:**
 - All about Proactive Adaptation,**

Scope of Adaptation :

- “Ways” - Speed (How Fast)
- Quality (How Well)
- “Means” - Use of Existing Resources
- Future System Development



Warfare Examples Using Existing “Means”:

- Environment (Choice)
 - Boyd’s OODA Loop: “Ways” (Speed & Quality)
 - Salamis, Trafalgar: “Ways” & Environment

Warfare Examples Using New “Ways” & “Means”:

Phalanx / Alexander the Great:

Minor modification of “Means” & “Ways”:

Vastly improved Effectiveness

- **Success** in warfare:
 - A function of **effectiveness**
 - A Measure of the **outcome** of the battle
- **Effectiveness** results from
 - The **combination of “Ways” & “Means”, ours & theirs, in the environment of contact**
= **Not** (necessarily) from the **performance capability of our systems (“Means”)**
- **However: Cost = f (Performance)**
Cost = f (Effectiveness)

Effectiveness is established:

- In the “Ways” & “Means” Trade-Space;
- Not: in the Performance & Cost Trade-

Improving Mission Effectiveness

1. Find Better “Ways” of Using Existing “Means”

2. Retain Current “Ways” but Develop Improved “Means”

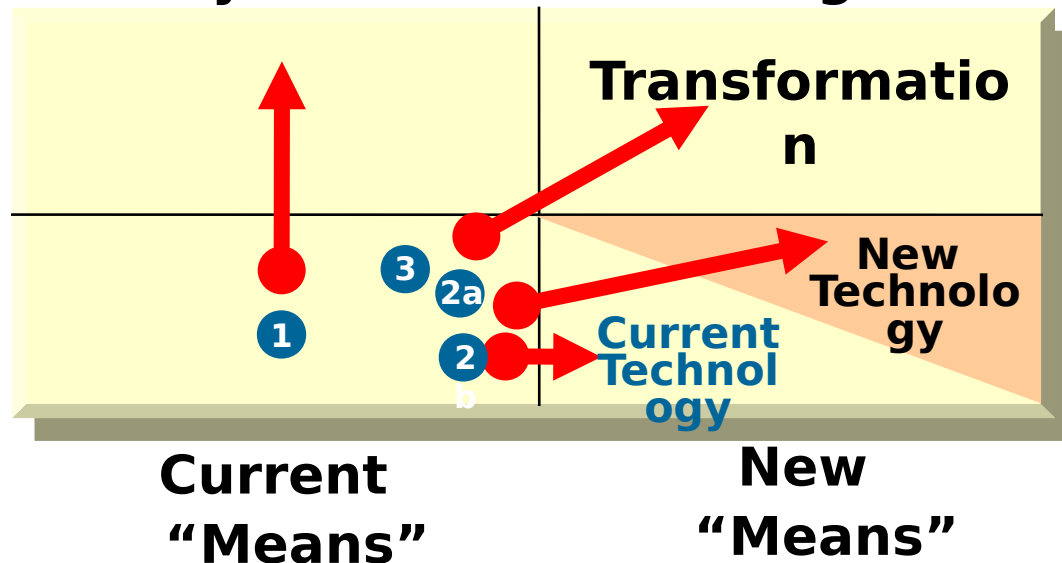
a. With Current Technology

b. With New / Advanced Technology

3. Develop New “Ways” to Take Advantage of New “Means”

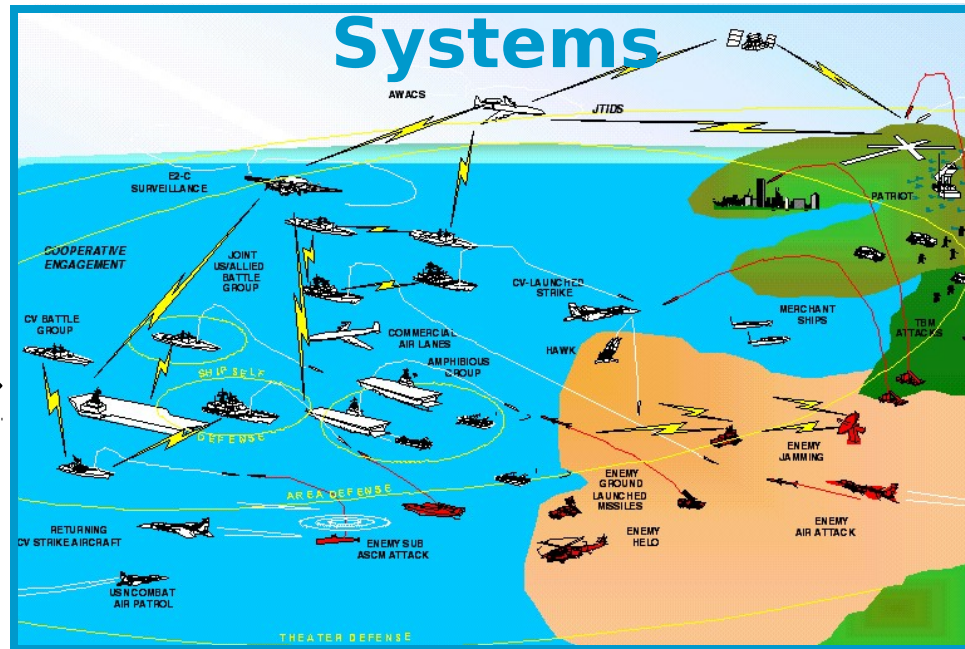
New “Ways”

Current
“Ways”



- **Systems Engineering - A Brief Review**
- **The Systems Spectrum:**
- **Complex Adaptive Systems (CAS)**
- ➔ • **Developing (Elements of) CAS**
 - **Systems “Engineering”(?) of CAS**

The Warfare System of Systems



Operations Development

Material Support

Personnel Support/Dev't

Requirements (MNS, O&D)

(ICD, CDD)

Material Development

Personnel Development

Personnel

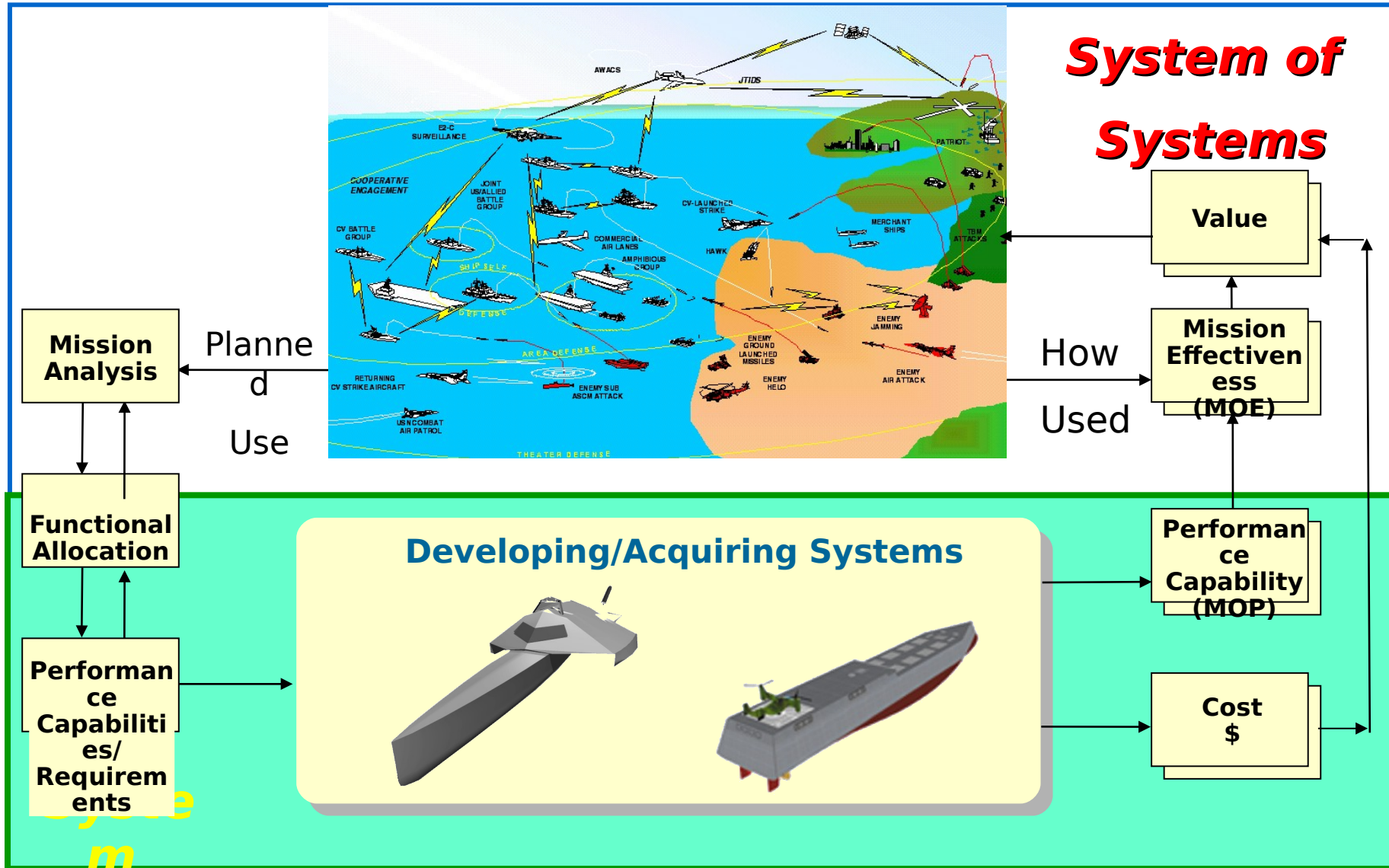
Manning

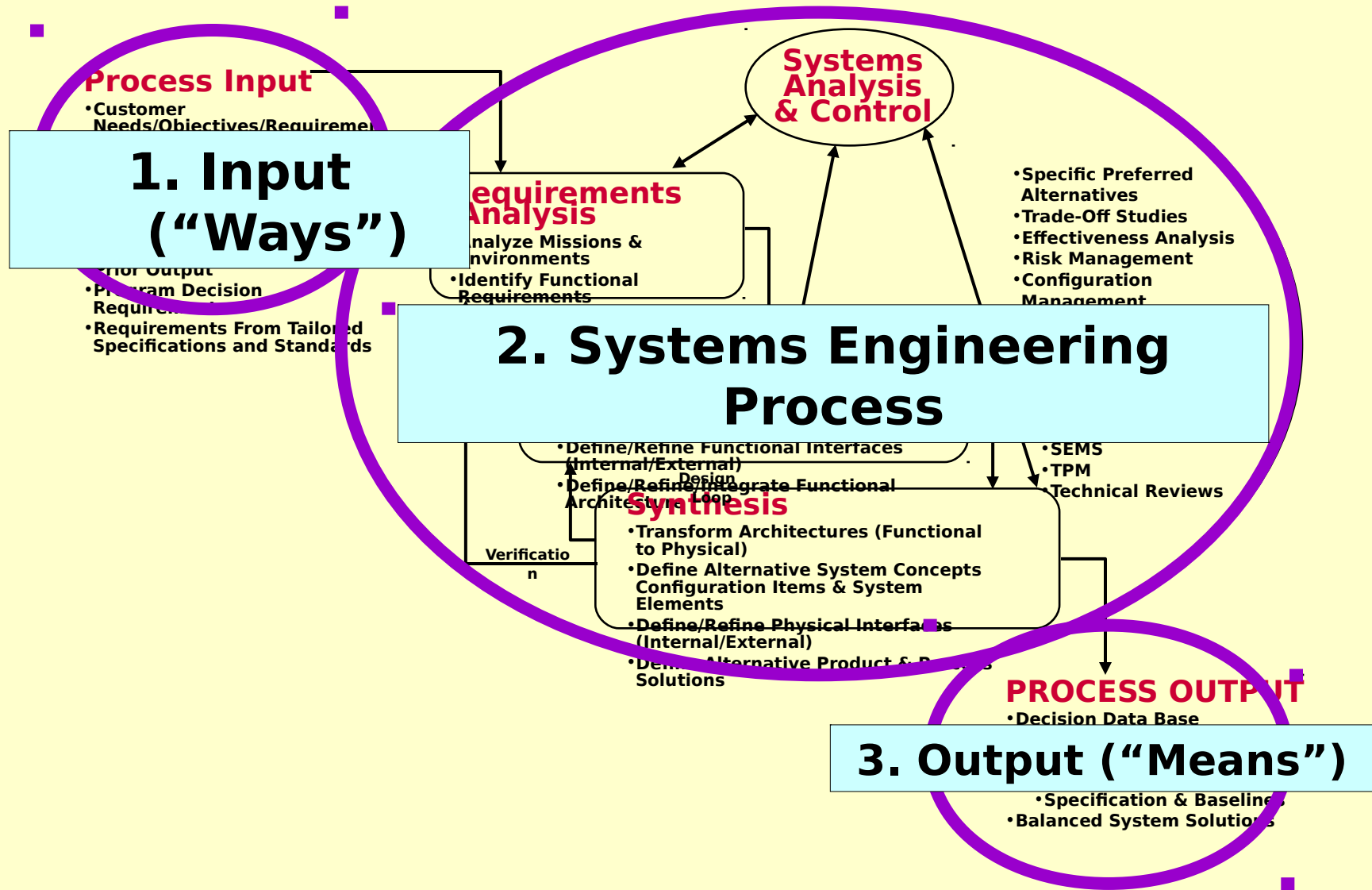
The Acquisition System

Ship System Development



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"Ways" Development

Process Input

- Customer Needs/Objectives
- Missions
- Measures
- Environmental Constraints
- Technology Baseline
- Prior Output
- Program Decision Requirements
- Requirements From Tailored Specifications and Standards

"Ways" & "Means" Trade-Space

- Define/Refine Performance & Design Constraints
- Define/Refine Functional Requirements

Requirements

- Decompose to Lower-Level Functions
- Allocate Performance & Other Limiting Requirements to All Functional Levels
- Define/Refine Functional Interfaces (Internal/External)
- Define/Refine Integrated Functional Architecture

Functional Analysis/Allocation

- Decompose to Lower-Level Functions
- Allocate Performance & Other Limiting Requirements to All Functional Levels
- Define/Refine Functional Interfaces (Internal/External)
- Define/Refine Integrated Functional Architecture

Synthesis

- Transform Architectures (Functional to Physical)
- Define Alternative System Concepts Configuration Items & System Elements
- Define/Refine Physical Interfaces (Internal/External)
- Define Alternative Product & Process Solutions

Systems Analysis & Control

- Specific Preferred Alternatives
- Trade-Off Studies
- Effectiveness Analysis
- Risk Management
- Configuration Management
- Interface Management
- Data Management
- Performance-Based Progress Measurement
- SEMS
- TPM
- Technical Reviews

PROCESS OUTPUT

- Decision Data Base
- Decision Support Data
- System Functional & Physical Architectures
- Specification & Baselines
- Solution Solutions

Concurrent
"Ways" & "Means"
Development:



The "Means"
Solution

"Means"
Development

For P-CAS, in particular... :



EXPERIENCE. RESULTS.

- Both performance capability and cost are design-dependent , require some system definition because
 - It is not possible to assess a system's performance capability or even technical feasibility without a design definition
 - It is rarely possible to develop reliable cost estimates for new systems solely on the basis of performance requirements.
- Cost information is crucial to make prudent decisions regarding quality versus quantity

• Valid performance predictions and cost estimates must be based on a **Design Definition**

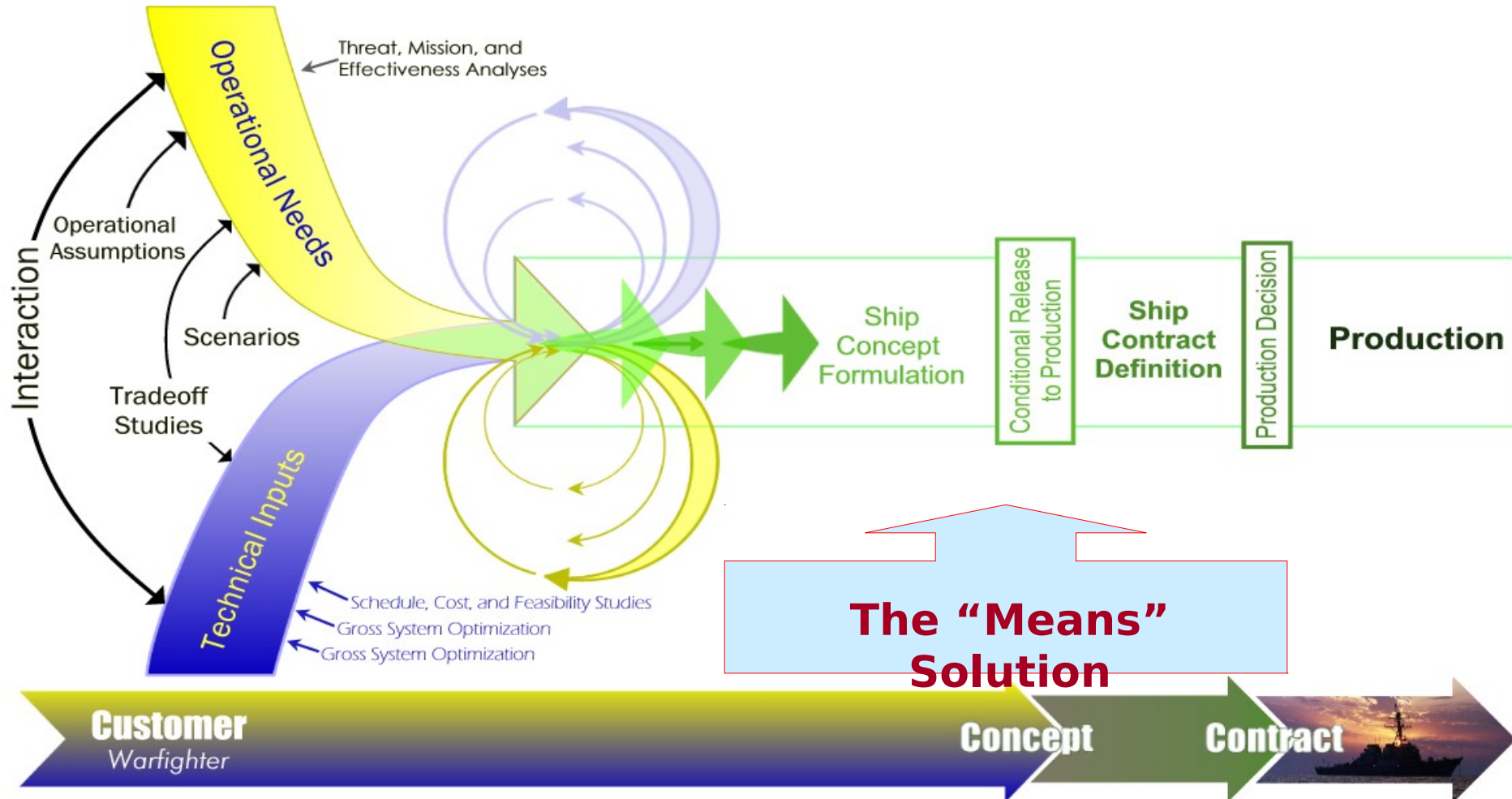
• The **“Ways” & “Means” Trade-Off** is incomplete if only the **Required Capability** is identified

A “Means” Solution must be defined !

The “Ways” & “Means” Trade Off



EXPERIENCE. RESULTS.

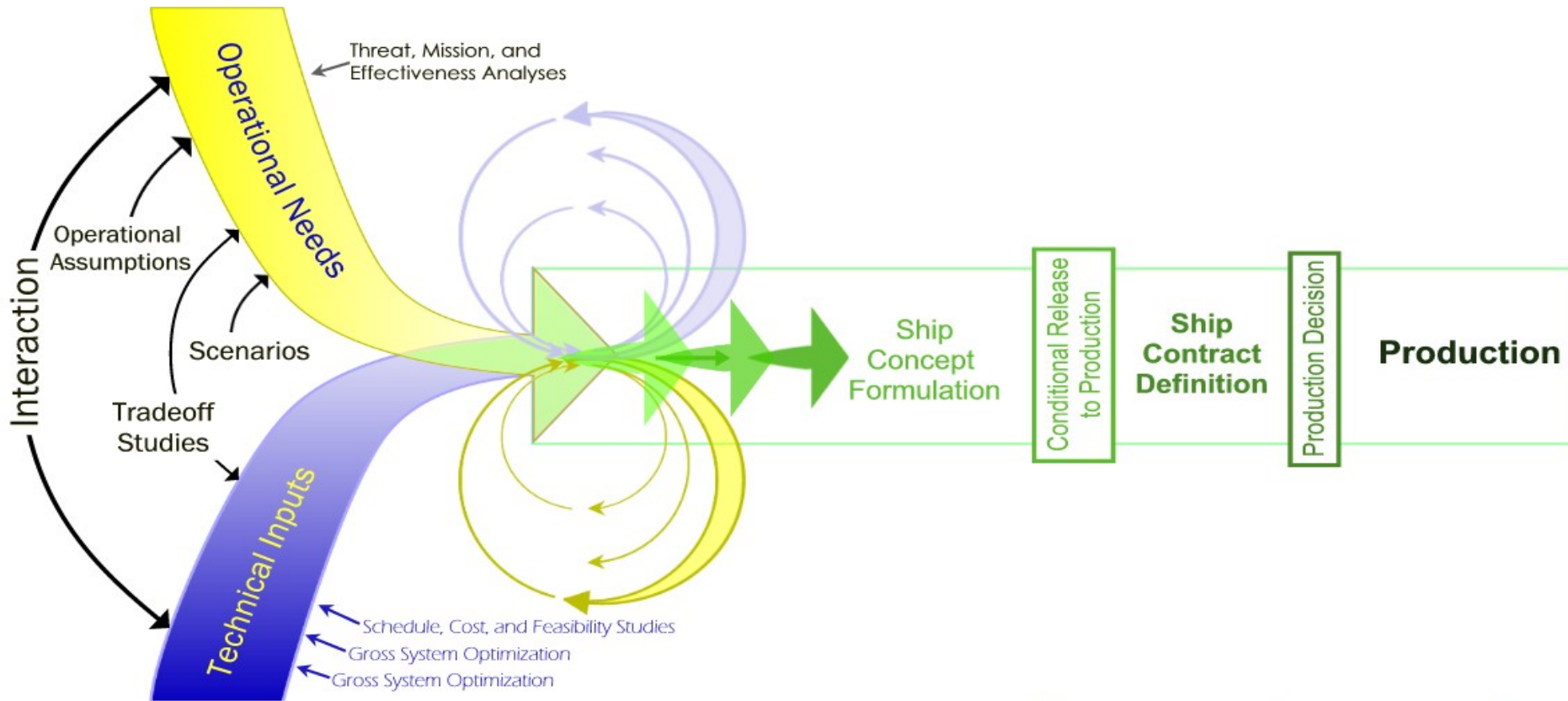


Solution - Based Acquisition

The “Ways” & “Means” Trade-Off



EXPERIENCE. RESULTS.



Credits:

NAVSHIPS 0900-060-0100, “Guide for Conducting Ship Concept Formulation”, Figure 2-4, page 2-16, 1969 A.D.

- **Systems form a Spectrum ranging**
 - **from Traditional Engineering Systems (TES)**
 - **to Complex Adaptive Systems (CAS)**
 - **CAS may be Reactive (R-CAS) or Proactive (P-CAS)**
 - **P-CAS are of special interest to the Defense Industry**
 - **TES display a strong link of System/"Means" Performance and Effectiveness**
 - **In Proactive CAS, this link is often very weak:**
 - **It is greatly diluted by**
 - **how and where we use systems ("Our Ways") and**
 - **the adversary's ways and means**
- Performance Requirements**

**(For Proactive Complex Adaptive Systems,
such as Warfare Systems, in particular...)**

- **Requirements must “float” until the Exploration of the “Ways” & “Means” Trade-Space has been completed**

Only the user can determine which combination of “Ways & Means” will be most effective

- **Completion entails the selection of the**
 - **“Means” Solution based on effectiveness, capability and cost**
- Therefore:**

“Definition before Acquisition”;

therefore: Solution-Based Acquisition